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7th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 14–18, 1999

Unusually wide plateau of the quantum Hall effect in a quasi bilayer hole system inside the p-GeSi/Ge/p-GeSi quantum well

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Abstract. An unusually wide plateau of the integer quantum Hall effect (for the filling factor ν = 1) has been revealed in a wide *p*-GeSi/Ge/*p*-GeSi quantum well. This plateau exists in one of two metastable states of the sample, for which a symmetric quasi-double-quantum-well system is formed inside the Ge layer due to the hole-hole repulsion. The plateau exists not only within a magnetic field range corresponding to the quantum-Hall liquid, but extends beyond it into a so-called quantized Hall insulator phase. According to the existing theories, this extra wide plateau may be indicative of a kind of disorder, characterized by a certain distribution of fluctuations in their size and carrier density.

Magnetic field dependence of the low temperature quantum magnetotransport in a 2D charge carrier gas is described by a series of alternating electron phases, each dependent on the degree and character of disorder in the system [1]. The *high disoder* system under weak magnetic field B exhibits a divergently growing longitudinal ρ_{xx} resistivity with decreasing temperature T, but a temperature independent classical linear $\rho_{xy}(B)$ Hall resistivity [2–5], this phase being called a Hall insulator [1]. A high (giant) negative magnetoresistivity is usually observed in this field range for high disorder systems. At the higher fields the Hall resistivity $\rho_{xy}(B)$ passes into a faint plateau of the quantum Hall effect (QHE), concomitant with a rather weak $\rho_{xx}(B)$ minimum, indicating a transition into a QH-liquid phase. This phase terminates with a transition to a high-field insulator phase, characterized again by a divergent $\rho_{xx}(B,T)$, but either divergent and T-dependent [3, 4], or finite linear [5] Hall magnetoresistance. The electronic phase transitions are marked with the node points, through which all the $\rho_{xx}(B)$ traces for different temperatures pass. In the *moderate disorder* system, with mobilities of the order of 10 m^2/V·s (implying an n-type GaAs-based system), quite distinct integer QHE (IQHE) plateaux are observed at milli-Kelvin temperatures with almost vertical interplateau transitions [6]. In the *most perfect* systems, with mobilities $\geq$ 100 m^2/V·s, the IQHE plateau widths decrease with increasing mobility, forming interplateau intervals of a quasi-linear $\rho_{xy}(B)$ dependence, which are in fact filled with the fractional QHE (FQHE) states [7]. IQHE in these systems terminates at a high field side with a linear $\rho_{xy}(B)$ dependent part broken by the FQHE peculiarities, and it is from this linear part the transition into an insulating phase occurs for the low disorder systems [8].

Since the IQHE plateau widths depend nonmonotonously on disorder the questions arise: what is the maximum IQHE plateau width possible and under what conditions would it realize? While the principal limit exists for the maximum IQHE plateau widths with filling factors $\nu > 1$, which is determined by a simple condition $\Delta\nu = 1$ (spin-split case) stemmed from the periodic intersections of the Fermi level with the Landau levels, the situation isn't that trivial for the $\nu = 1$ case. At first sight, maximum width possible for this plateau is determined by the same condition $\Delta\nu = 1.5{-}0.5 = 1$, implying that

delocolized states are located in energy close to the centers of both the lowest Landau levels. In fact, the bending upward of this plateau observed until recently [9] always started at $\nu > 0.5$. Anyhow, it was implied conventionally that this plateau couldn't extend into a high field insulating phase over the phase transition point, since the plateau at the fundamental $\rho_{xy} = h/e^2$ value has been considered the feature of the QHE-phase only.

Some recent results contradict this postulate. First, it was found that the $\nu = 1/3$ FQHE plateau extends beyond the high field phase transition point [10]. Later similar result was obtained for a $\nu = 1$ IQHE plateau in a GaAs/AlGaAs heterostructure with mobility as low as $\mu = 1.1$ m^2/V·s [11]. Both results [10, 11] have been obtained for n-type conductivity. It is worth noting that investigations of a $\nu = 1$ QH state in a low mobility GaAs/AlGaAs n-type heterostructure may be problematic due to a small g-factor resulting in a hardly resolved spin sublevels (considering that transition between 0^+ and 0^- sublevels is responsible for this QH state). Probably by that reason a more spectacular result was achieved on a p-type heterostructure (Ge/GeSi) [12] with the $\nu = 1$ QH plateau reaching from 2.5 T till the maximum 10 T field measured.

As it follows from a theoretical analysis of the insulator neighboring of the QH phase [13] based on a random network of paddles, the QH plateau indeed may extend into an insulating phase with its width being dependent on the relative abundance of different density puddles, which depends in turn on the distribution of potential fluctuations. Interplay between percolation via the network and coupling of the puddles by tunneling results in that the smaller puddle sizes allow a larger regime of the quantized Hall insulator phase. Considering the high sensitivity of the plateau width to the details of the disorder potential in the sample, together with a very poor number of experimental results available, we think that new results on this account would be of a great importance. We have observed an unusually wide Hall plateau in the low temperature measurements performed on Ge/p-$Ge_{1-x}Si_x$ multi-quantum-well selectively doped heterostructures [14], and it was revealed under rather specific conditions — as a component of a bistable state.

Here we analyze these results in view of the T-dependence of $\rho_{xx}(B)$ to separate different electronic phases. The results were obtained on the samples 451b4 and 451a4 of a big family investigated: see [14, 15] for a more detailed sample description. These two samples differ from the others by rather wide wells of 35.5 nm and lower hole densities $p_s = 1.4 \cdot 10^{15}$ m^{-2} (other parameters: number of repetitions 36, $x = 0.097$ and $\mu = 1.4$ m^2/V·s). A bistable behavior of these samples was revealed in the high field range at low temperatures characterized by two metastable states (see Fig. 1(a) for the sample 451b4; sample 451a4 is cut from the same wafer and exhibits similar results): (i) a QH state with holes divided into two 2D sublayers in each Ge layer and (ii) a classical state with undivided hole gas in a layer. The former state implies an existence of some self-stabilizing mechanism, probably connected with the weak tunneling through the barrier between two equivalent states in the sublayers. Going out of the balance drives the system into the state with a single conducting gas in a Ge layer and to destruction of the QH regime. This implies the change of the potential profile in the well due to the hole gas redistribution in the direction normal to the interface [14]. The bistable behavior in asymmetric double-quantum-wells (DQW) was revealed in a number of works [16].

Comparing our results for the DQW state with the results [12] a good resemblance could be seen, although we have a somewhat lower precision for the ρ_{xy} value within the plateau due to the multilayered structure of the samples and the metastability of the quasi-DQW state: with a very weak (here) or absent [12] $\nu = 2$ (related to a single 2D gas) QH state an extremely wide $\nu = 1$ plateau exists; the low field border of the plateau is located in the

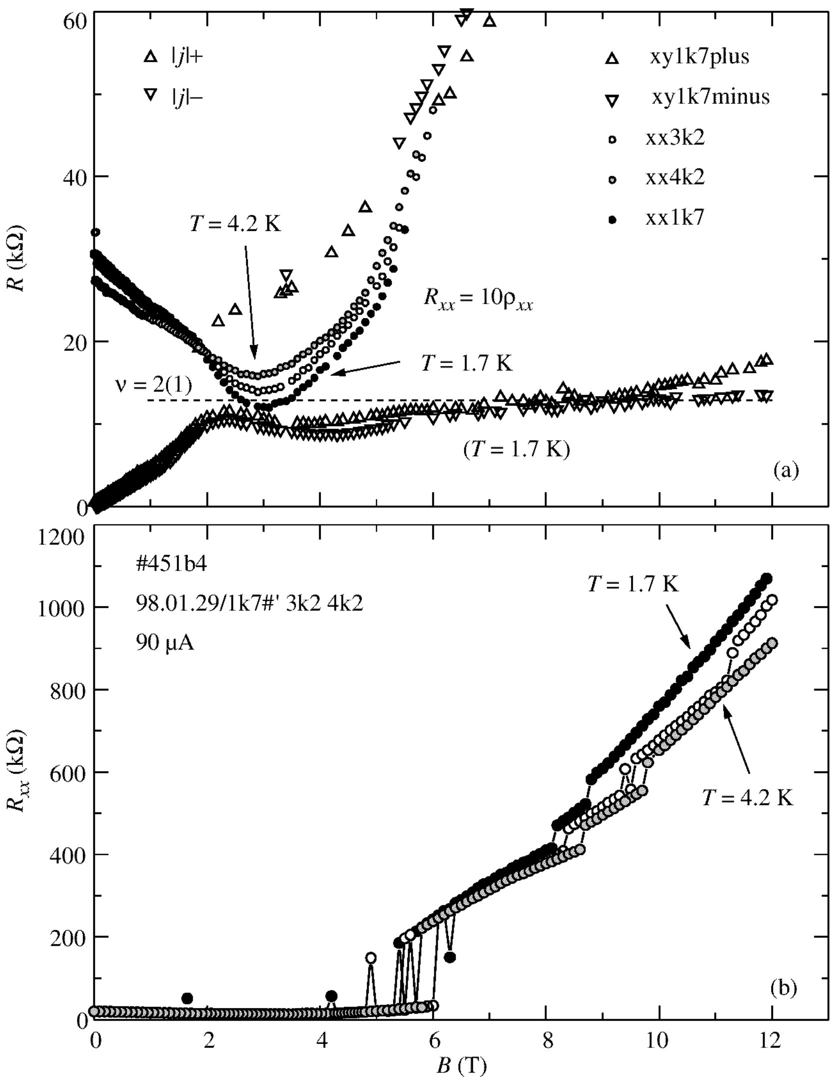

Fig. 1. (a) Bistability in the Hall resistance of sample 451b4. The dash line marks the ρ_{xy} value for the first plateau, calculated per a Ge layer ($h/2e^2$). The scale for ρ_{xx} is a factor of 10 enlarged. (b) $R_{xx}(B)$ as measured for $T = 1.7$, 3.2 and 4.2 K.

vicinity of the low field node point present in the $\rho_{xx}(B, T)$ set of traces. As for the high field node, the unstable $\rho_{xx}(B)$ behavior hampers to determine it exactly, but we can see for sure that this node does exist in the vicinity of $B = 6$ T: it follows particularly from that the $\rho_{xx}(B)$ trace for the lowest temperature measured $T = 1.7$ K is the lowest one in the minimum at $B = 3$ T, but it is the highest one at the high field region (Fig. 1(b)). Thus the plateau extends above the QH phase into the state of quantized Hall insulator [13] in our results, as well as in [12]. Also we can see that the value of resistance in the high field node is several times higher than it is in the low field node. Analyzing other works we can conclude that the values of ρ_{xx} are approximately equal in both nodes for the high

disorder samples [2–5], but the low field node goes down relative the high field node for the lower disorder, receding from the fundamental value h/e^2: see [9], also such an asymmetry appears in [12] for the higher hole densities regulated by the gate voltage. We've observed a higher difference in the ρ_{xx} values in the nodes that reflects a lower disorder in our sample than in [12]. The latter is confirmed by the existence of a weak $\nu = 2$ peculiarity and by the lower $\rho(B = 0)$ values.

Finally, it's worth noting that, like in our work, the measurements in [12] were done on the GeSi/Ge/GeSi heterosystem with a p-type conductivity, but with a substantial difference: in contrast to our samples with symmetrically doped QWs, their structures were single side doped, that resulted in an initially asymmetric QW potential relief. Similar potential profile is expected to exist in our samples in the single-component metastable state. Surprising is that we've obtained a qualitatively different result, namely a classical behavior, in this state. This yields an additional argument in favor of an important role of the disorder characteristics for the description of samples and emphasizes insufficiency of characterizing the sample by such macro parameters as the mobility and the carrier density only.

The work is supported by RFBR, Grants No 98-02-17306 and 99-02-16256.

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